



Power Supply Design Seminar

Topic 1 Presentation:

High Power Factor and High Efficiency — You Can Have Both

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Topic 1

High Power Factor and High Efficiency: You Can Have Both

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Agenda

- ◆ Definition of power factor and discussion of the applicable standards
- ◆ Effect of the power factor on power-distribution losses
- ◆ Benefits of active PFC
- ◆ Effect of the input-voltage range on PFC efficiency
- ◆ Configurable PFC topologies
- ◆ The buck PFC: a solution for universal input-voltage applications
- ◆ Conclusions

Definition of Power Factor: A Quick Review

- ◆ PF = Real Power / Apparent Power
- ◆ Real Power = $\frac{1}{T} \int_0^T v i dt$
- ◆ Apparent Power = $V_{\text{RMS}} \times I_{\text{RMS}}$
- ◆ Definition valid for arbitrary current and voltage waveforms

Linear and Nonlinear Loads

- ◆ Sinusoidal source, linear load
 - Both the voltage and the current are sinusoidal but not in phase; power factor less than unity
 - PF known as : $\cos(\Phi)$ or “displacement power factor”
- ◆ Sinusoidal source, nonlinear load
 - PF is determined by phase angle and harmonics
 - Harmonics increase apparent power, the power factor also less than unity
 - Reducing harmonics increases the power factor

Standards for Power-Factor Correction

◆ EN61000-3-2

- Focuses on line-current harmonics
- Four categories according to different end equipments
- Most power supplies are Class D

◆ Energy Star[®]

- Power supplies with greater than or equal to 100-W input power must have a true power factor of 0.9 or greater at 100% of rated load when tested at 115 V, 60 Hz

◆ Universal-input power supplies need to meet requirements of both standards

Power Factor and EN61000-3-2 Class D

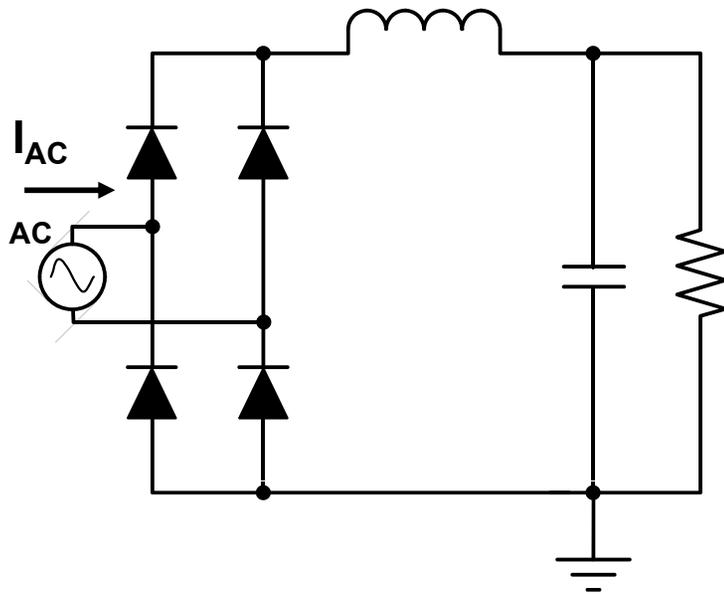
- ◆ Meeting EN61000-3-2 harmonic standard is not enough to meet the Energy Star power-factor requirement

Harmonic Order n	75 W < P < 600 W Maximum Permissible Harmonic Current (mA/W)
3	3.4
5	1.9
7	1.0
9	0.5
11	0.35
13	0.269
15 ≤ n ≤ 39	3.85/n

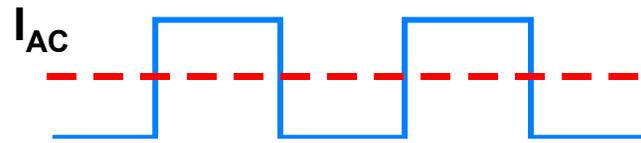
$$\text{PF} = F_{\text{Displacement}} \times F_{\text{Distortion}} \quad \xrightarrow{F_{\text{Displacement}} = 1} \quad \text{PF} = \frac{I_1}{\sqrt{\sum_{n=1,3}^{39} I_n^2}} = 0.726$$

Harmonics for Energy Star

- ◆ A power supply drawing square-wave line current is well within Energy Star PF limits but will fail the IEC harmonic-content standard



PF = 0.9



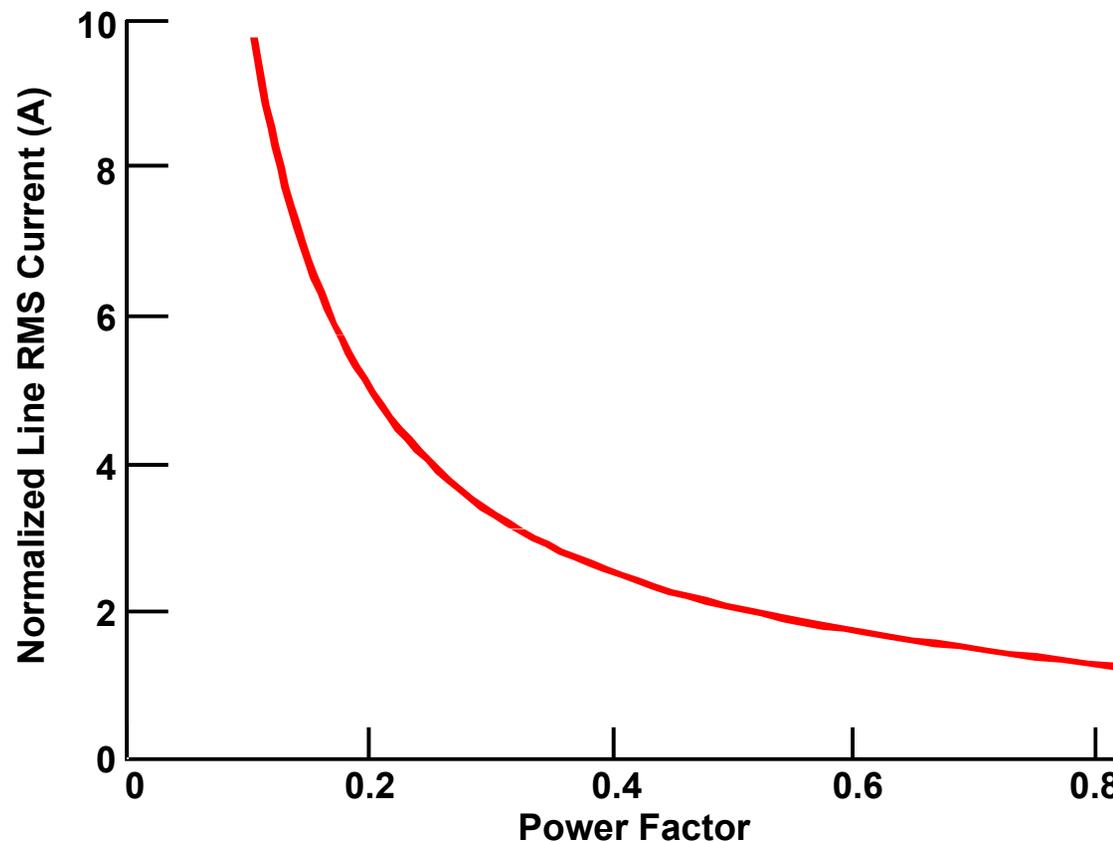
$$I_{11} = 0.56 \text{ mA} / \text{W} > 0.35 \text{ mA} / \text{W}$$

Meeting Both Standards

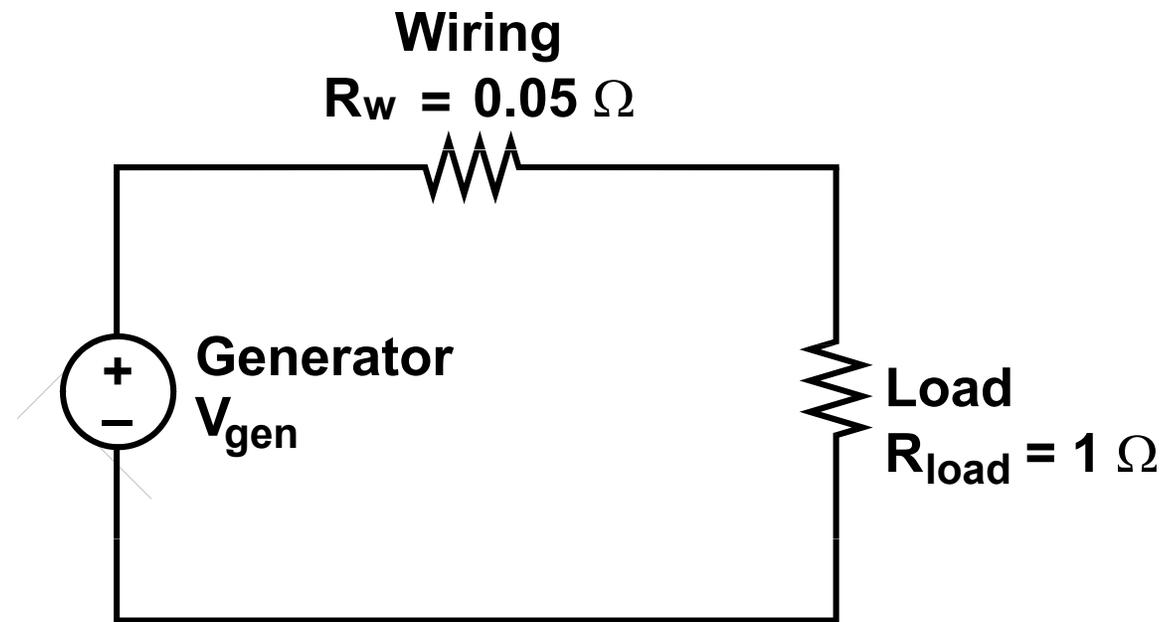
- ◆ The PFC circuit must increase the PF to the Energy Star limit **AND** attenuate the harmonics below the limits of EN61000-3-2

The Power Factor and the Power-Distribution Losses

- ◆ If the PF is low, an increase in RMS current is required to deliver a given amount of power



Normalized Power-Distribution Losses

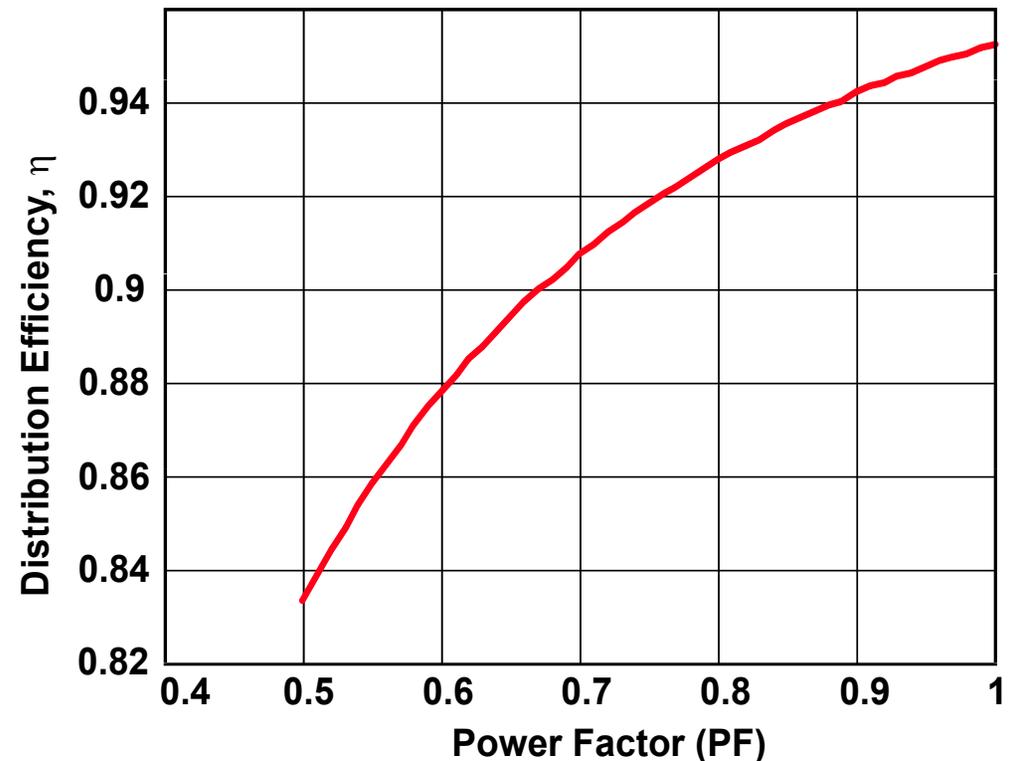


Where:

V_{gen} = Effective AC source voltage
 R_w = Distribution wiring resistance
 R_{load} = Load resistance

Effect of the Power Factor on Power-Distribution Losses

- ◆ PFC reduces distribution losses
- ◆ Assuming 5% distribution loss, the system will break even if the efficiency of the PFC circuit is 0.953



Direct Benefits of PFC/Harmonics Attenuation

- ◆ Meet the requirements of EN61000-2-3 and Energy Star
- ◆ Higher power factor
- ◆ Allows higher power draw from 115-V lines
 - 0.5 PF = 719 W, 0.9 PF = 1294 W (intermittent rating)
- ◆ Reduced stresses on neutral conductors
- ◆ Improved electrical system distribution efficiency
(Only if the PFC efficiency is high enough!)
- ◆ Reduced VA rating of standby power systems

Indirect Benefits of Active PFC/Harmonics Attenuation

- ◆ Facilitates power supply holdup
- ◆ Universal input voltage capability
(85 to 265 VAC)
- ◆ Improved efficiency of downstream
DC/DC converters

Active PFC/Harmonic Attenuation Circuits

- ◆ Most popular active PFC circuit: The boost converter
- ◆ This additional conversion stage adds power dissipation
- ◆ **Efficiency of the PFC stage is strongly dependent on the difference between the input and the output voltage**

Analysis of the Boost PFC Efficiency

- ◆ To examine the effect of the difference between the input and output voltages on efficiency, we define the “Boost Factor” BF:

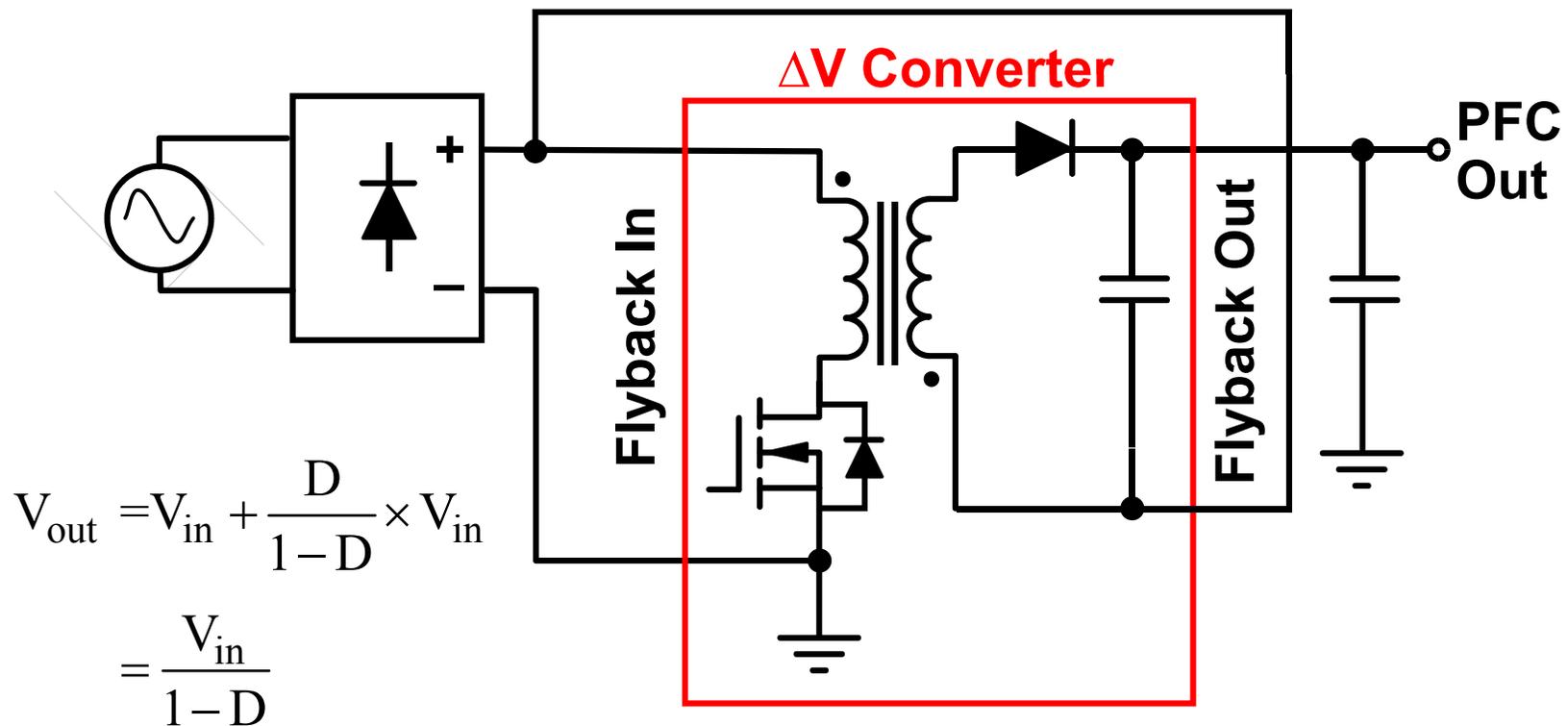
$$BF = \frac{V_{out}}{V_{in(pk)}}$$

Analysis of the Boost PFC Efficiency

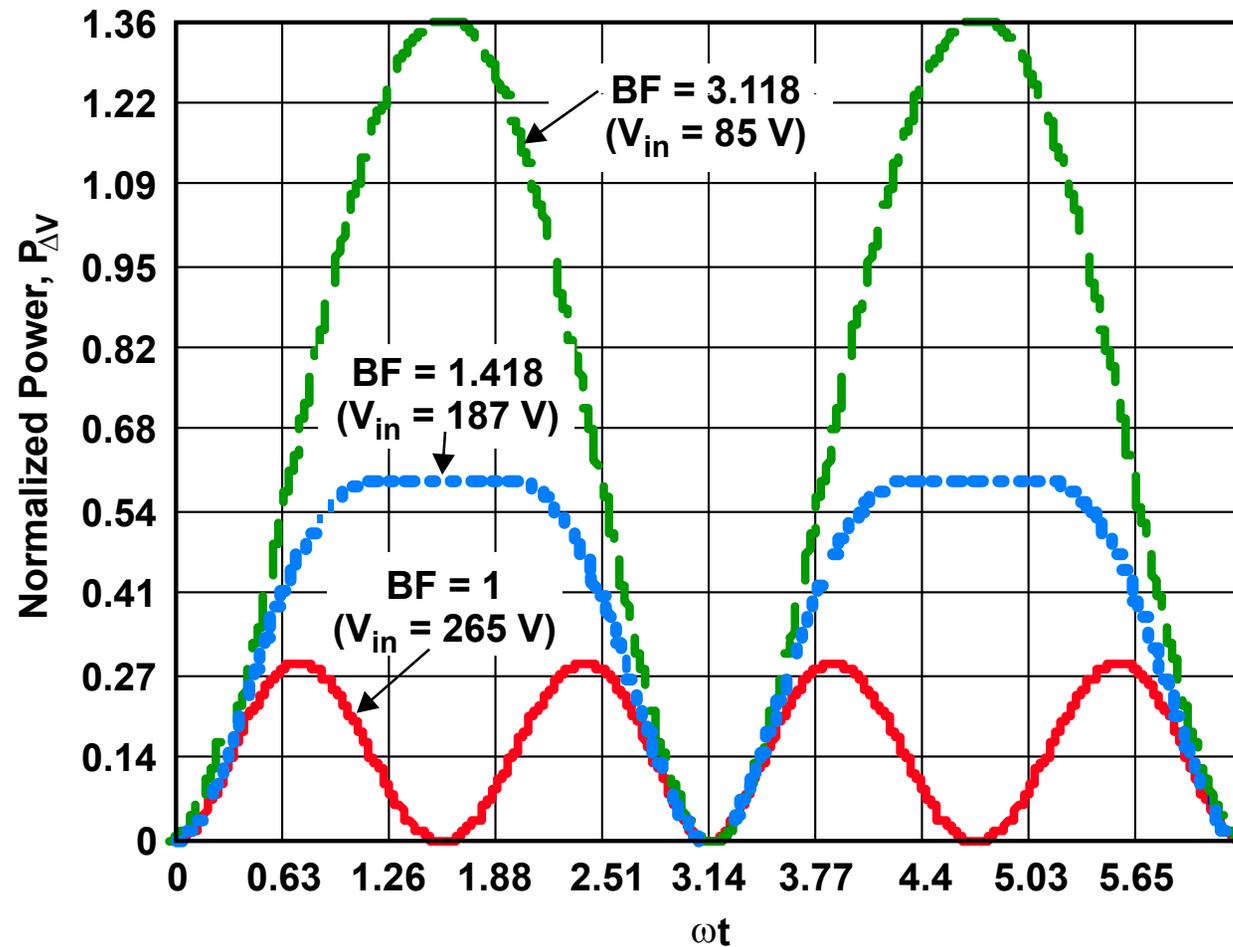
- ◆ A nonisolated converter is similar to an autotransformer
- ◆ Separate the power flow by separating the power transferred directly to the output from power processed by the PFC circuit
- ◆ Emulate the PFC boost converter by adding the output of a flyback converter (“ ΔV converter”) in series with the rectified line-input voltage
- ◆ The model is equivalent to a boost converter

The ΔV Converter

- ◆ A little algebra shows that the DC transfer function of the proposed circuit is identical to that of a boost converter

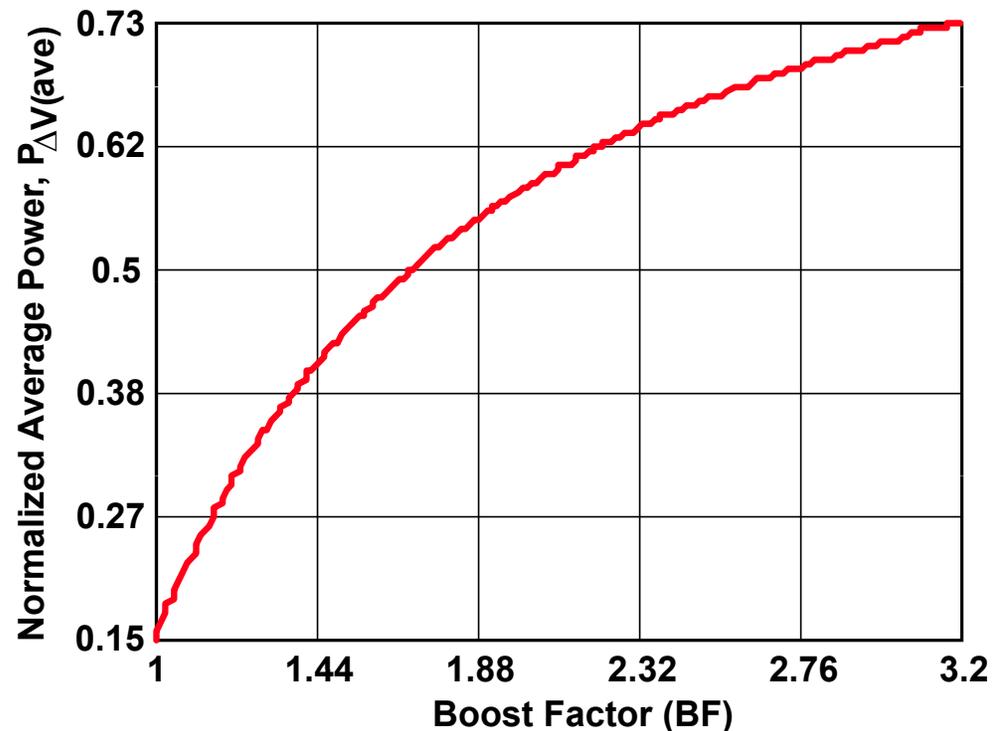


Peak-Power Rating of the ΔV Converter as a Function of Input Voltage



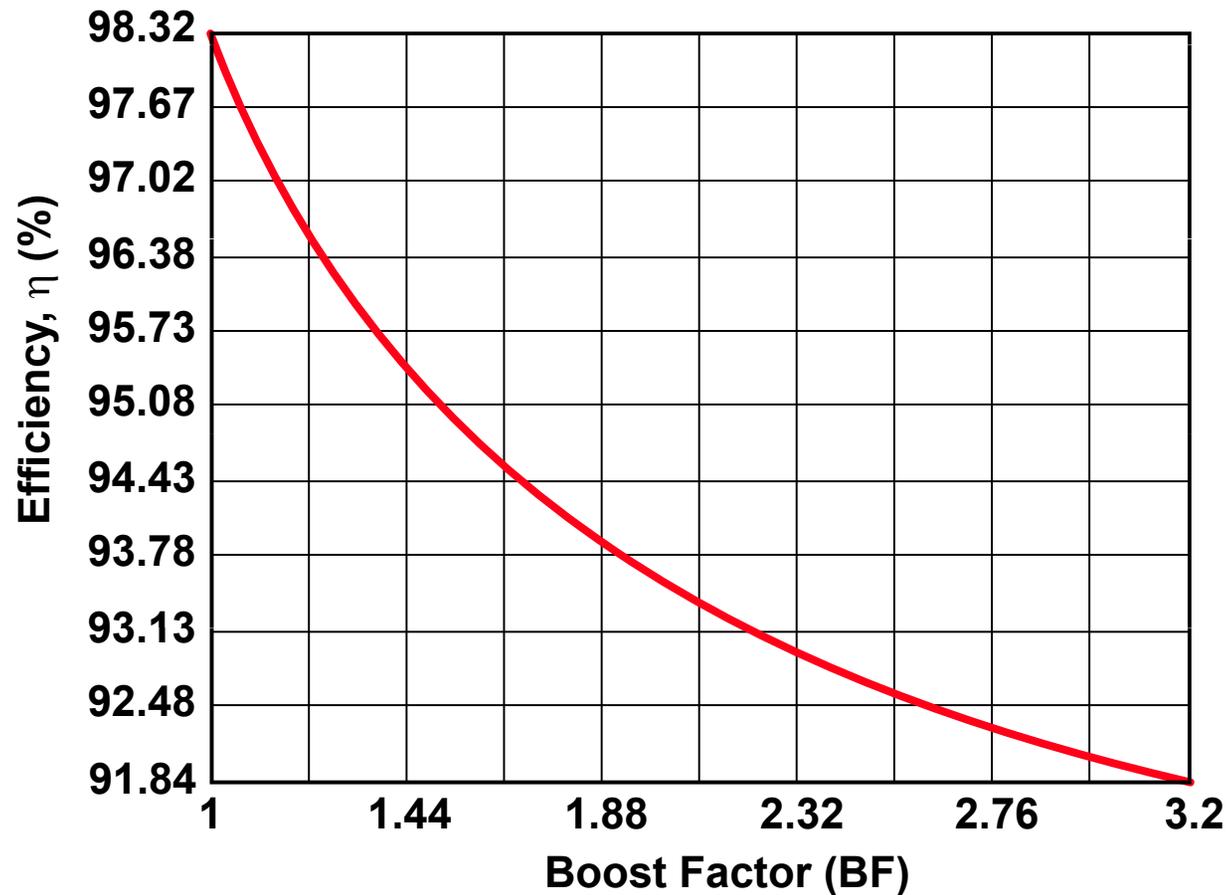
Average-Power Rating of ΔV Converter as a Function of Input Voltage

- ◆ The average power delivered by the ΔV converter is a strong function of BF
- ◆ An increasing BF also corresponds to an increase in boost-PFC size and cost



Overall PFC Efficiency versus BF

- ◆ ΔV converter efficiency = 90%



Discussion of the Results

- ◆ As the boost factor increases, the converter processes more power and the efficiency decreases
- ◆ Component ratings and converter efficiency are driven by the lowest operating Boost Factor
- ◆ For “local” voltages
 - Designed for Boost Factor of 1.417
 - ΔV -converter average- and peak-power ratings are 40.1% and 58.9% of the PFC-stage output power
- ◆ For universal input voltage
 - Designed for Boost Factor of 3.118
 - ΔV converter average- and peak-power ratings are 73% and 136% of the PFC-stage output power

Universal-Input Voltage Issues

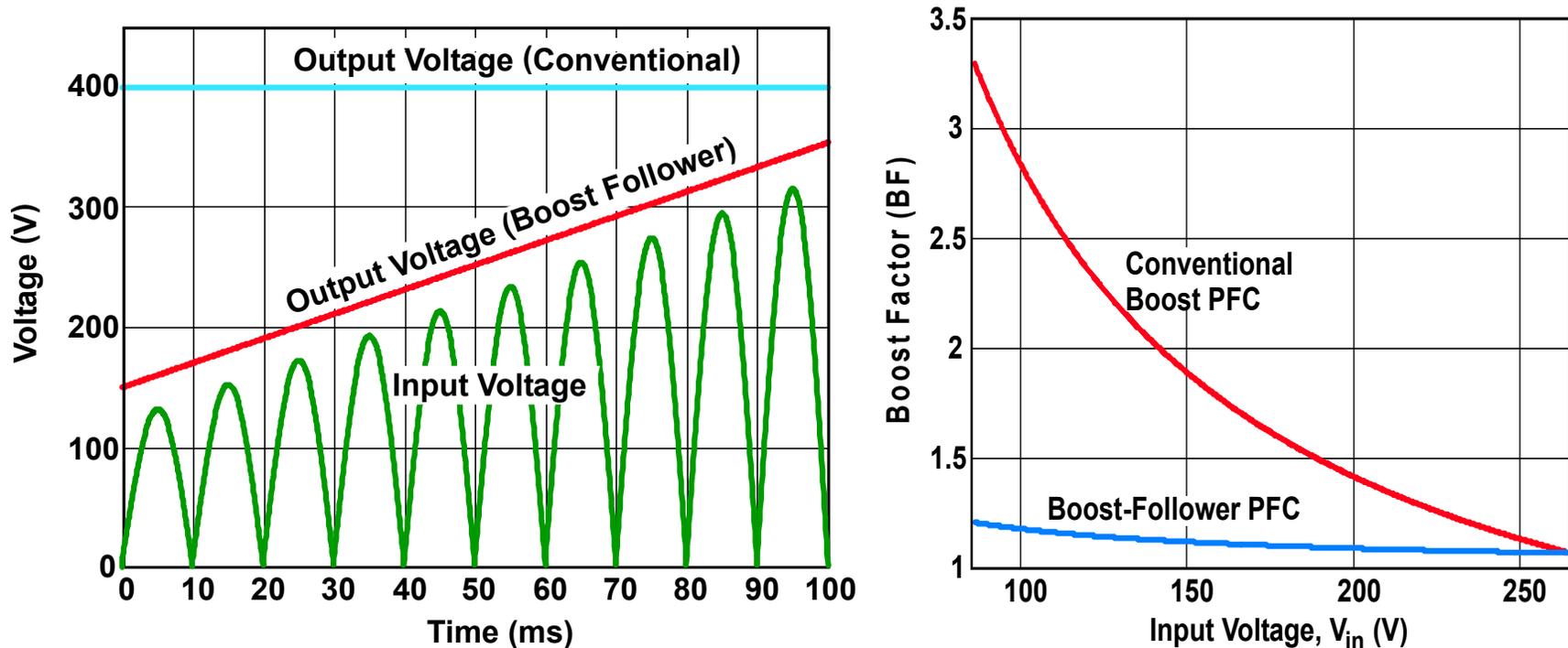
- ◆ Must or preference?
- ◆ Logistics, commonality
- ◆ “Regional” products
 - HVDC bus voltage
 - BOMs for the PFC converter and the downstream DC/DC converter(s)
- ◆ Trade-offs

Improving PFC Efficiency: Reduce Boost Factor!

◆ Ideas:

- Boost follower
- Configurable PFC stage
 - ◆ Three-level PFC
- Buck instead of boost PFC

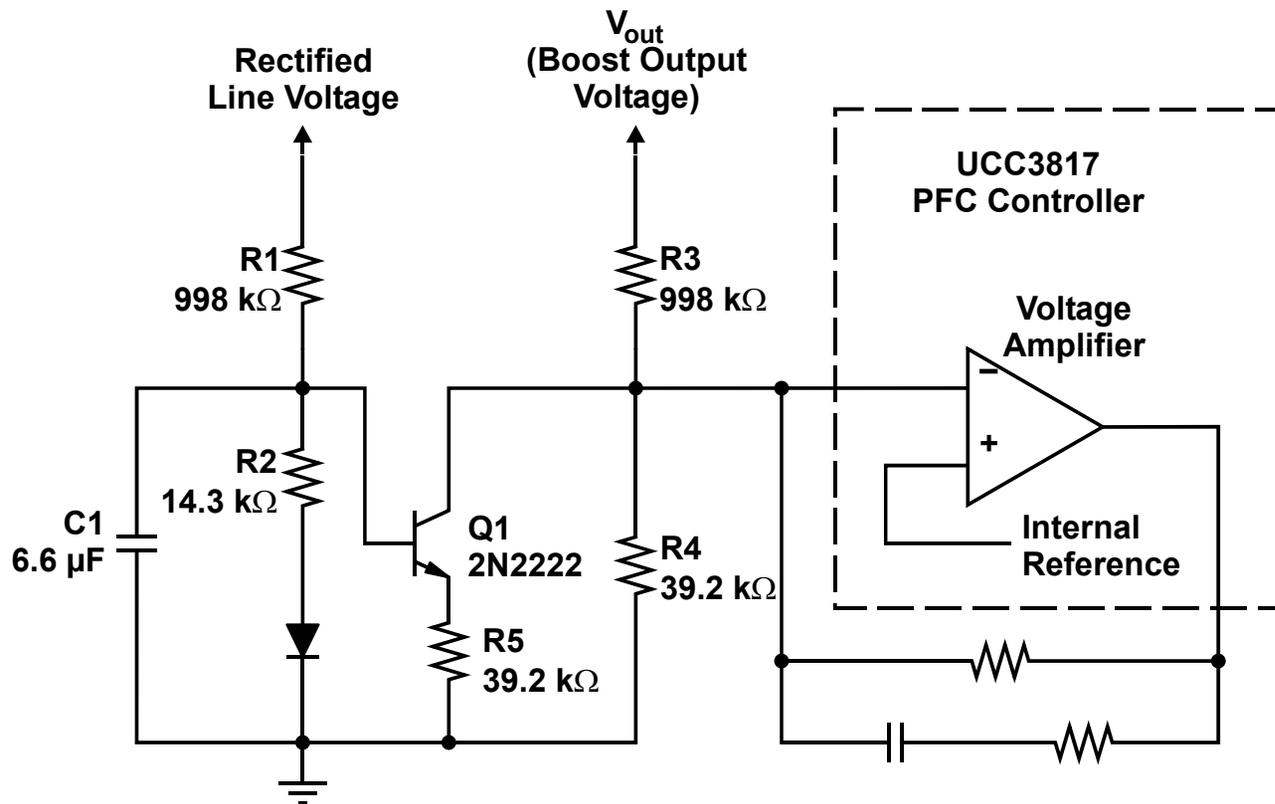
Boost-Follower PFC



- ◆ Conventional PFC maintains same output voltage for different line voltages, the boost factor is 3.3 at 85-V input
- ◆ Boost follower PFC changes its output voltage according to the AC line voltage (following AC line voltage)
- ◆ Boost factor is greatly reduced and efficiency can be improved but V_{out} is not constant

Boost-Follower PFC Implementation

- ◆ By adjusting the voltage-sensing divider network, output voltage can be changed with most off-the-shelf PFC controllers



“Simple circuitry gets that old PFC controller working in a boost-follower PFC Application,” By Michael O’Loughlin

Design Considerations

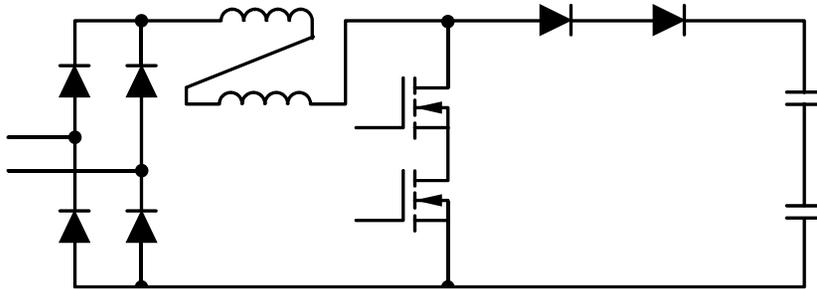
- ◆ “Boost Follower” reduces BF but:
 - Transformer turns ratio in the downstream converters must be lower, so:
 - ◆ Primary currents are higher, VA rating increases
 - ◆ Higher voltages on rectifiers, higher V_f
 - ◆ Larger filter inductor
 - ◆ Larger capacitors on the HV bus

Configurable Topologies

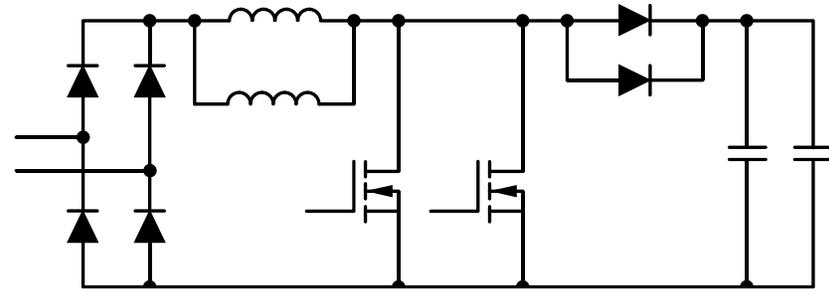
- ◆ Use identical components for both 115-V and 230-V inputs
- ◆ Same HVDC bus voltage
- ◆ Configuration on assembly line for 115 V or 230 V
- ◆ Nearly equal efficiencies for 115-V or 230-V operation

“Ideal” Configurable PFC

High line-input configuration

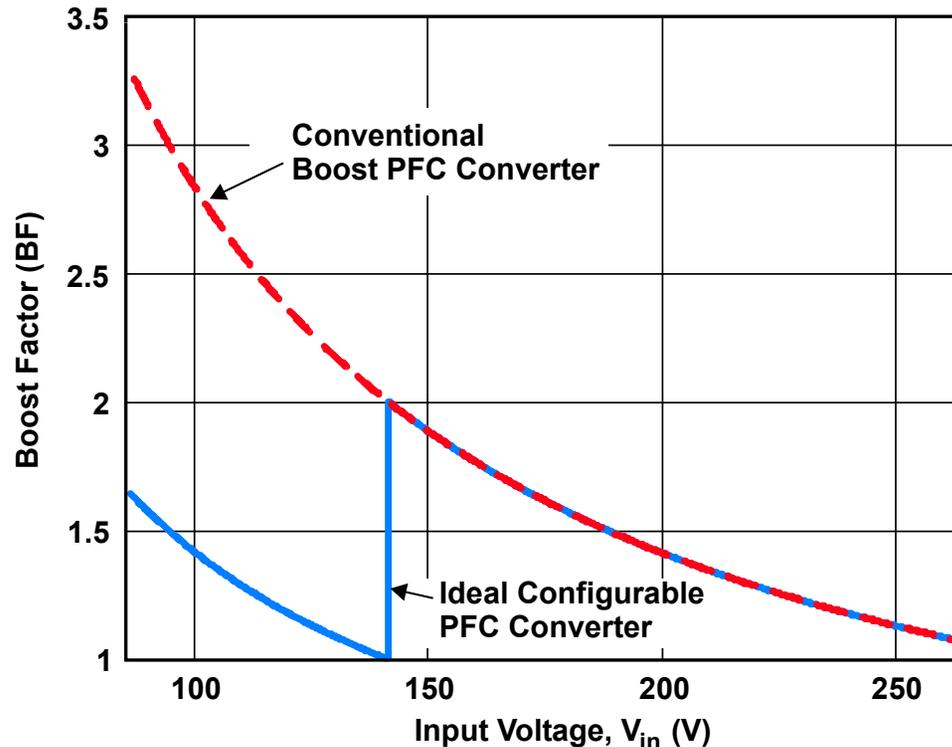


Low line-input configuration



- ◆ At high line input, the MOSFETs, diodes, and inductors are in series
- ◆ Output voltage is equal to the peak of the high line voltage (same as conventional PFC)
- ◆ Equal stresses on the converter components at either “High” or “Low” line-input configuration!
- ◆ At low line input, the MOSFETs, diodes, and inductors are in parallel
- ◆ Output voltage is only half the peak of the high line voltage

Boost Factor of Ideal Configurable PFC



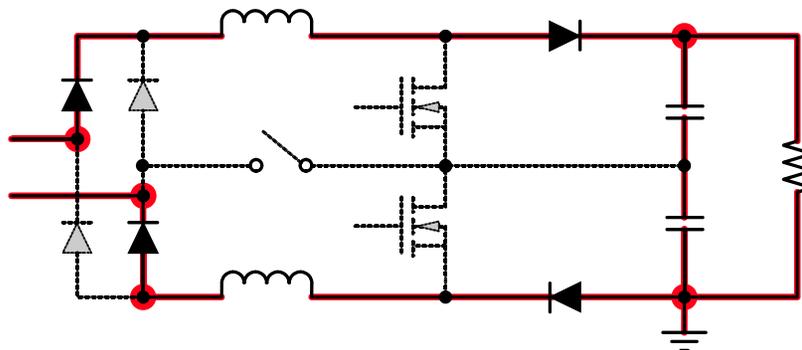
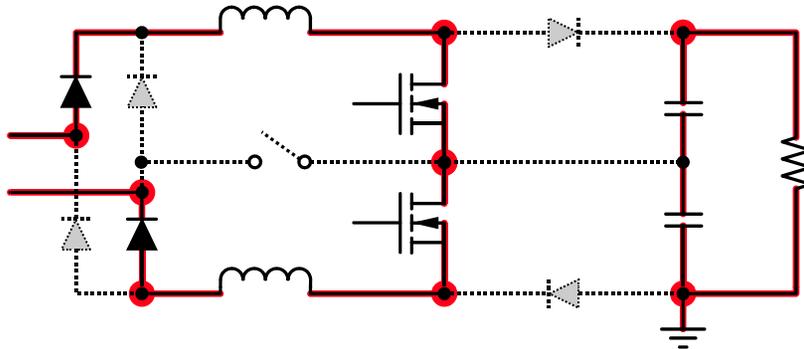
- ◆ At “high” line-input condition, the BF and the output voltage are the same as for a conventional PFC
- ◆ At “low” line-input condition, the BF and the output voltage are half the values of a conventional PFC

“Real-Life” Solutions

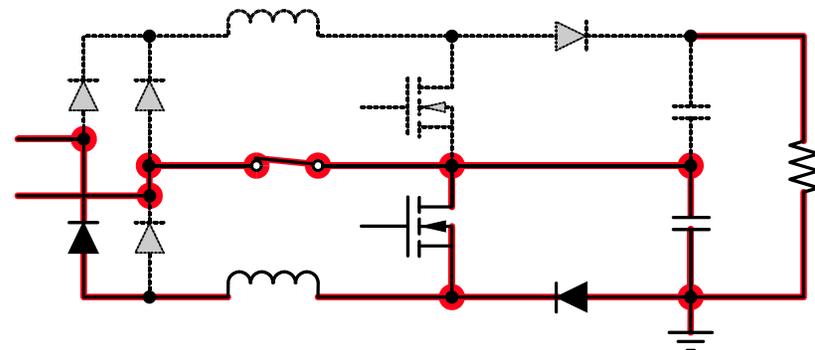
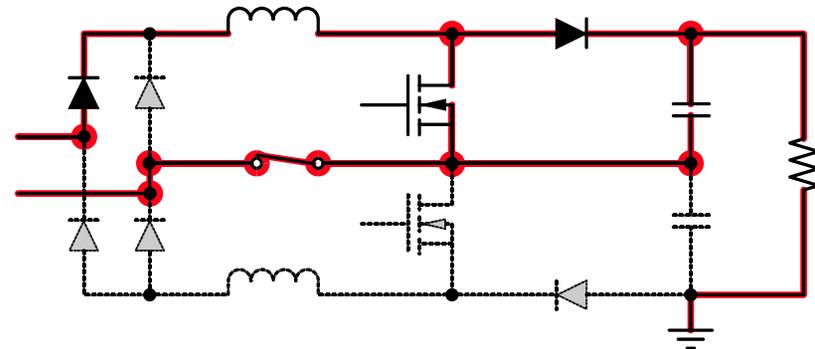
- ◆ The “ideal” circuit is not practical
 - Voltage balancing for series devices
 - Driving circuit for series circuits
- ◆ Practical circuits will be less efficient than the ideal

Configurable Three-Level PFC

- ◆ High line-input condition: two boost PFCs are in series

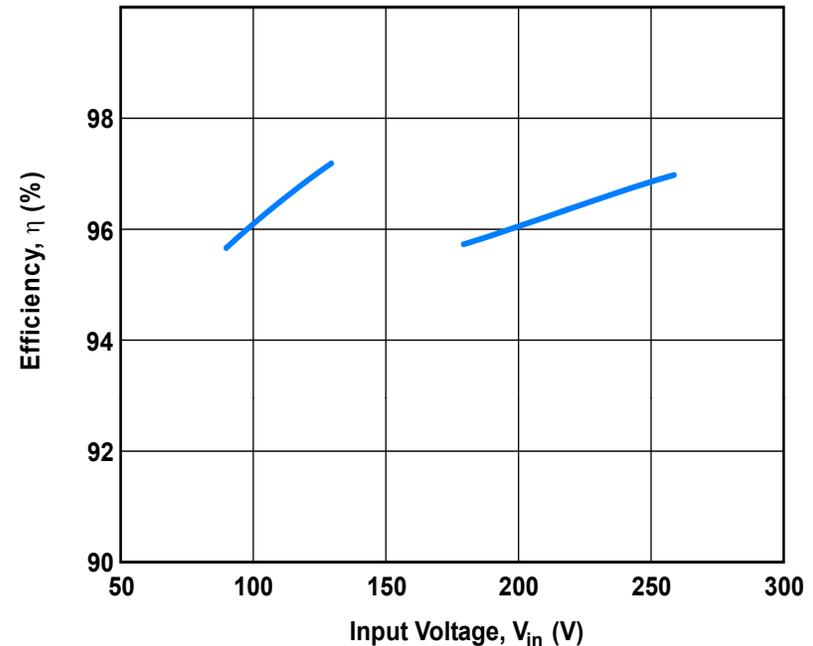
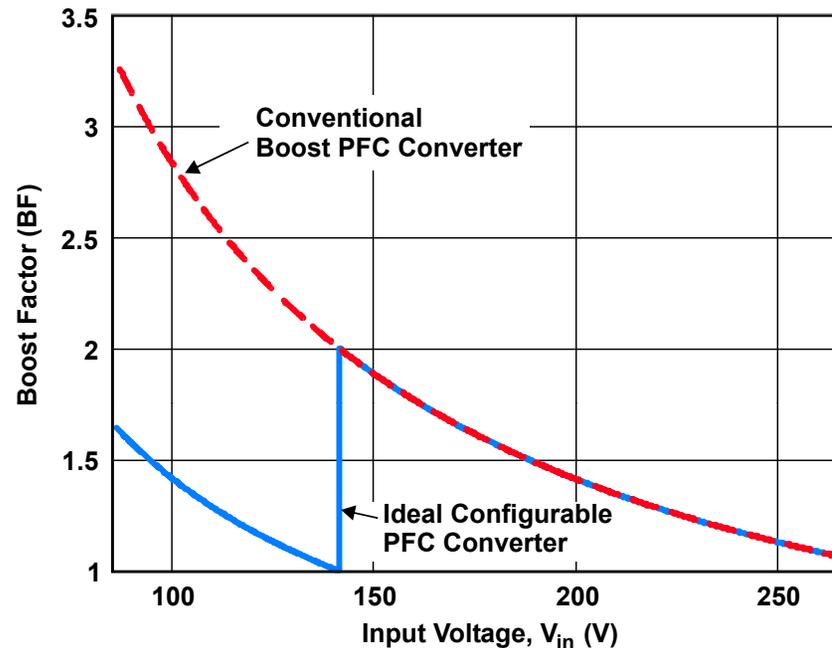


- ◆ Low line-input condition: only one boost PFC is operating at each half line cycle



Note: Output-bus voltage does not change for different configurations

Boost Factor and Efficiency Estimation



- ◆ Configurable three-level PFC maintains same output voltage for different line conditions
- ◆ At low line input, each boost PFC operates half-line cycle and the equivalent output voltage is half of the total PFC output voltage
- ◆ This reduced output voltage reduces the boost factor at low line input and improves efficiency

Benefits and Challenges

◆ Benefits

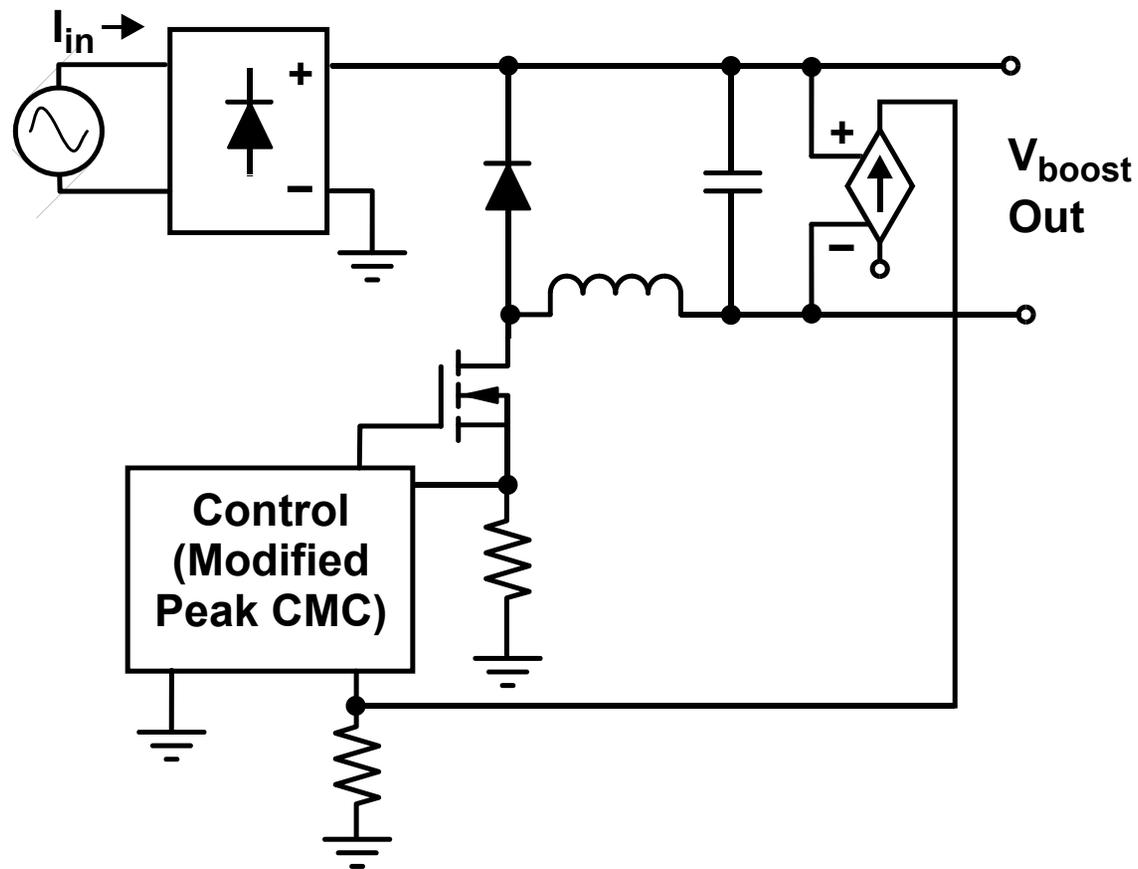
- Reduced boost factor improves overall system efficiency
- Three-level structure, a lower-voltage switches and diodes can be used to improve efficiency
- At low line conditions, the bridge is reconfigured as a doubler (bridge diodes can be paralleled)

◆ Challenges

- At low line input, each boost PFC only operates half of the line cycle (component utilization)
- Devices referenced to different grounds: drive, current sensing
- Voltage balancing on the output capacitors

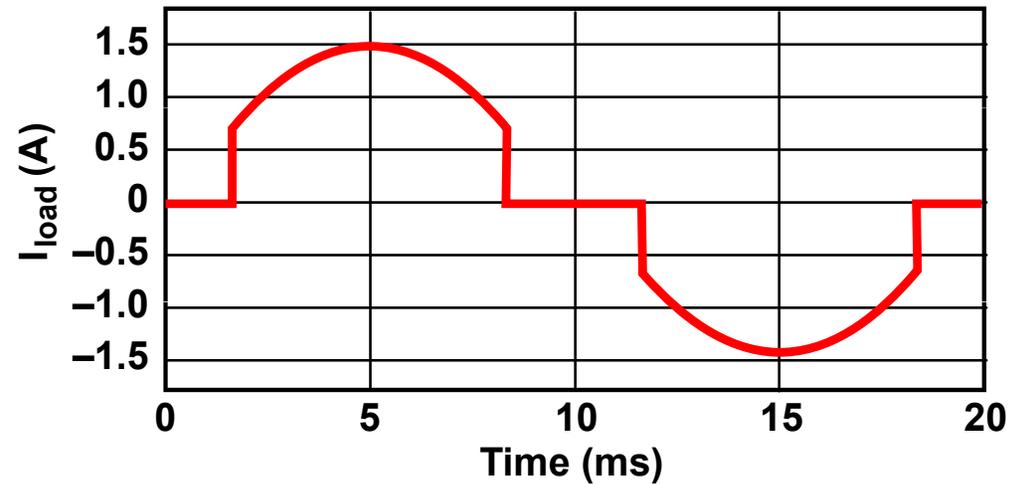
The Buck PFC

- ◆ A buck converter can also shape the input current
- ◆ Handles least power at lowest input (“Buck Factor”)

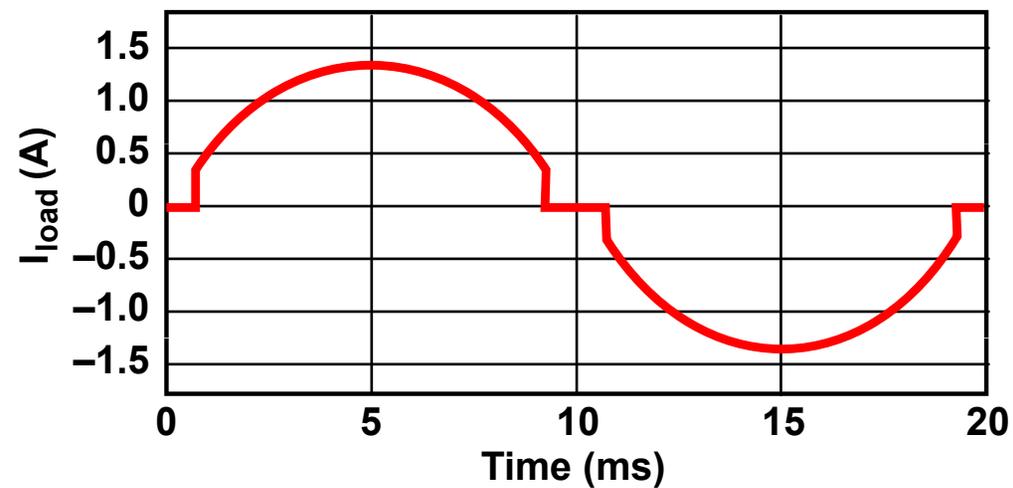


Idealized AC-Line Current with a Buck PFC

Low Line Input
(Normalized input
current)



High Line Input
(Normalized input
current)



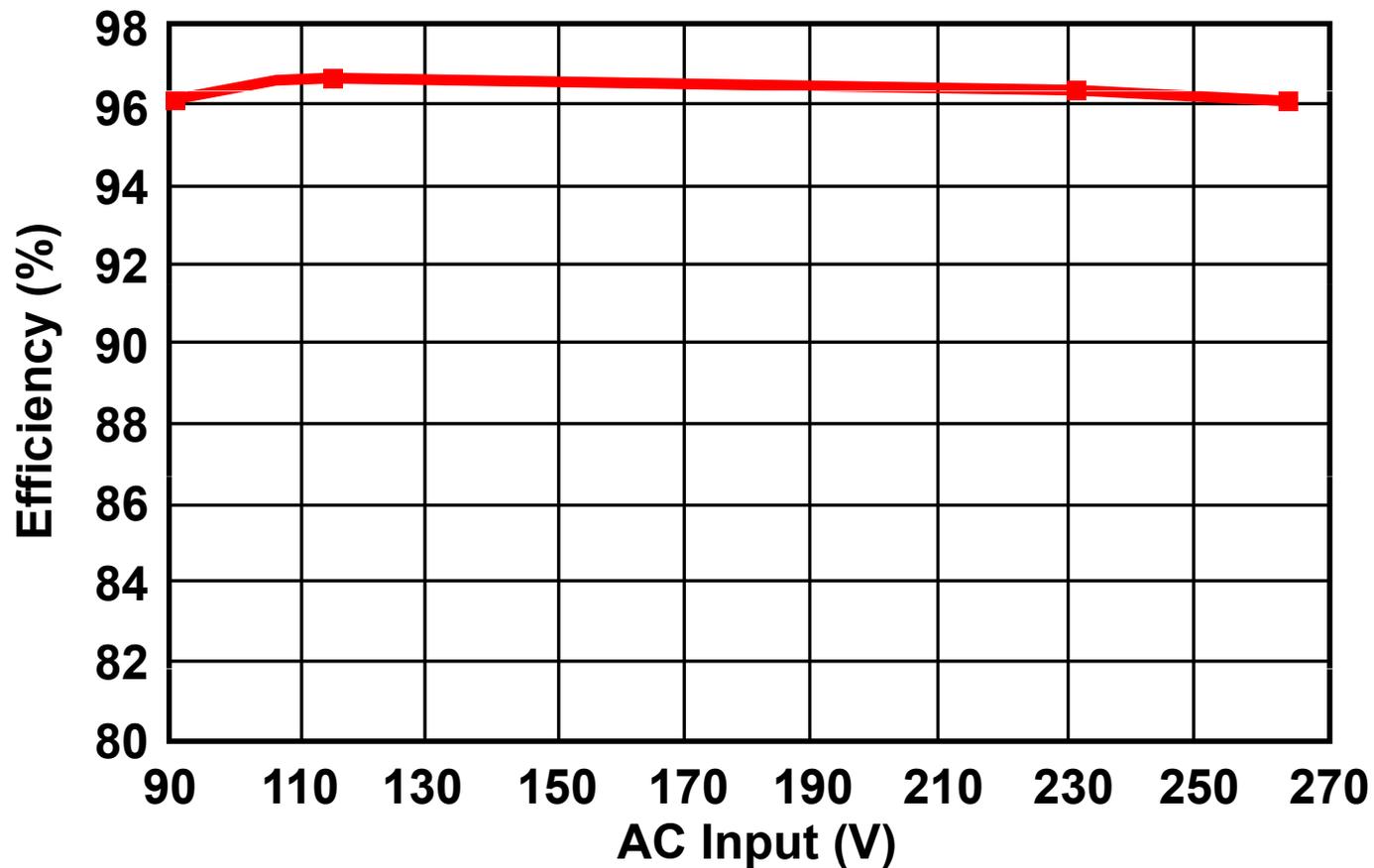
Buck PFC and Prevailing Standards

- ◆ The buck PFC draws current only if the input voltage is higher than the output voltage
- ◆ The optimal output voltage for universal input voltage is 80 V
- ◆ Waveform is “ugly” – but passes both EPA and IEC standards

Benefits of the Buck PFC

- ◆ Solves the problem of low efficiency at low input voltage
- ◆ Allows optimization of the downstream DC/DC converter
- ◆ Inherent inrush-current control
- ◆ “Gentler” on the HV diode than the boost converter it replaces

Efficiency of a 90-W Buck PFC versus the AC-Input Voltage



Conclusions

- ◆ PFC provides many benefits but adds losses that are strongly affected by the Boost Factor
- ◆ Reconfigurable-PFC topology is available that can reduce the effective BF and use the same components for both 115-V and 230-V lines—others to be invented?
- ◆ It remains to be seen if the pressure for ever higher efficiency will drive adoption of more complex topologies
- ◆ The buck PFC is an attractive solution for universal input voltages at power levels below 600 W

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